The Rocket Equation and Travel in the Solar System

By John V. Peters (4-16-2026)

What can the Rocket Equation tell us about space travel within our solar system?

But first, what is the Rocket Equation?

It is an equation developed in 1903 by a Russian high school math teacher named Konstantin Tsiolkovsky with an interest in rockets. The simple equation gives the relationship of the mass of the fueled rocket to the unfueled rocket mass:

$M_i \ / \ M_f = e^{\Delta V / Ve}$ or e raised to the power of (delta v/Ve)

Mi = the fueled mass of the rocket ship in kilograms

Mf = the unfueled mass of the rocket ship in kilograms

e = the exponential number e = 2.7182818…

deltla v = the velocity change required, in kilometers per second

Ve = the rocket engine's exhaust velocity, in kilometers per second

Often, the equation is arranged as

Mi = Mf x e^(delta v/Ve) to show that the fueled mass of the rocket ship is equal to the unfueled mass x a factor

defined by e^(delta v/Ve). Every kilogram of unfueled rocket mass requires a number of kilograms of fuel defined by the fuel factor of the Rocket Equation.

Setting the terms for our equation

We want to find the fuel factors for travel to and from our solar system planets.

We need a value for our rocket exhaust velocity and the delta v required for a round trip to each planet in our solar system.

One of the highest rocket exhaust velocities at present is the SpaceX Raptor-3 rocket engine used in the SpaceX Starship. We will use the vacuum exhaust value for this rocket engine, 3.4 kilometers per second.

For the delta v required to reach and return to earth from our moon and each solar system planet we will use the data from the attached delta v map of the solar system.

The Tyranny of the Rocket Equation

Let's consider the tyranny of the Rocket Equation. An example will illustrate this tyranny. The one-way trip to the moon requires a change of velocity or delta v of 14.66 kilometers per second, first speeding away from earth and then slowing to a landing on the moon. The fuel factor for this trip is e^14.66/3.4 or 75. A round-trip to the moon has a fuel factor of e^29.32/3.4 or 5,561 which is equal to [e^14.66/3.4]^2. For a two-way trip, you double the delta v required and the fuel factor result is the square of the fuel factor for the one-way trip.

In short, increases in the delta v lead to enormous increases in the fuel required.

Now, the numbers

The following calculations assume a single ship starting on earth, traveling to its destination planet, landing there (or traveling close to the planet in the case of the gas giants), and returning to land back on earth.

We will see the shocking numbers that result from applying the Rocket Equation.

The round trip delta v values of earth's moon and our solar system planets, arranged from lowest to highest delta v or velocity change required, are as follows:

Trip	delta v (km/s)	fuel factor
Earth to Moon and back	29.32	5,561
Earth to Mars and back	36.62	47,600
Earth to Mercury and back	46.28	815,670
Earth to Uranus and back	77.24	7,350,000,000
Earth to Neptune and back	80.70	20,300,000,000
Earth to Venus and back	85.58	85,400,000,000
Earth to Saturn and back	91.86	541,500,000,000
Earth to Jupiter and back	131.56	6.4 x 0^16

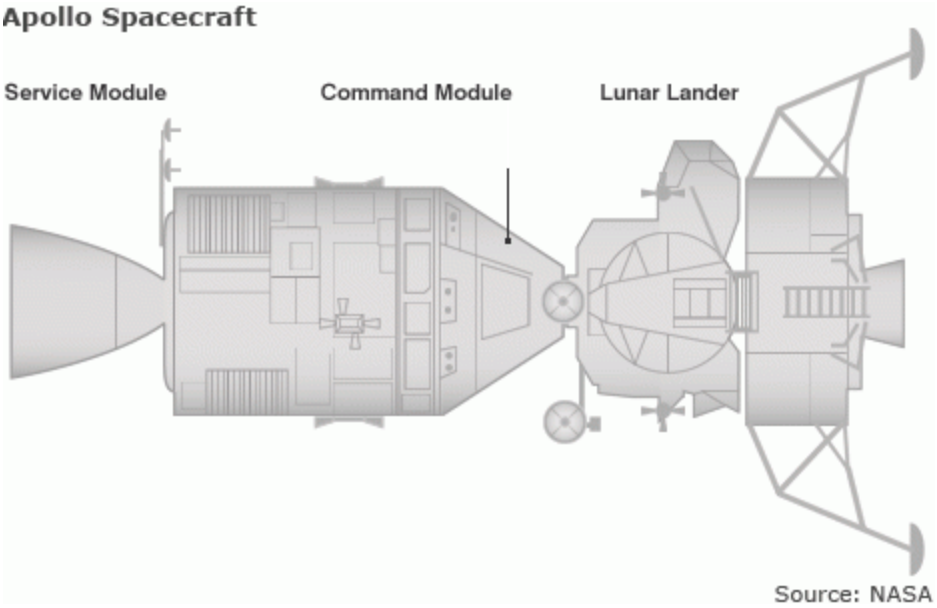
The obvious conclusion is that no single ship can travel to our solar system planets and back or even to our moon and return to earth.

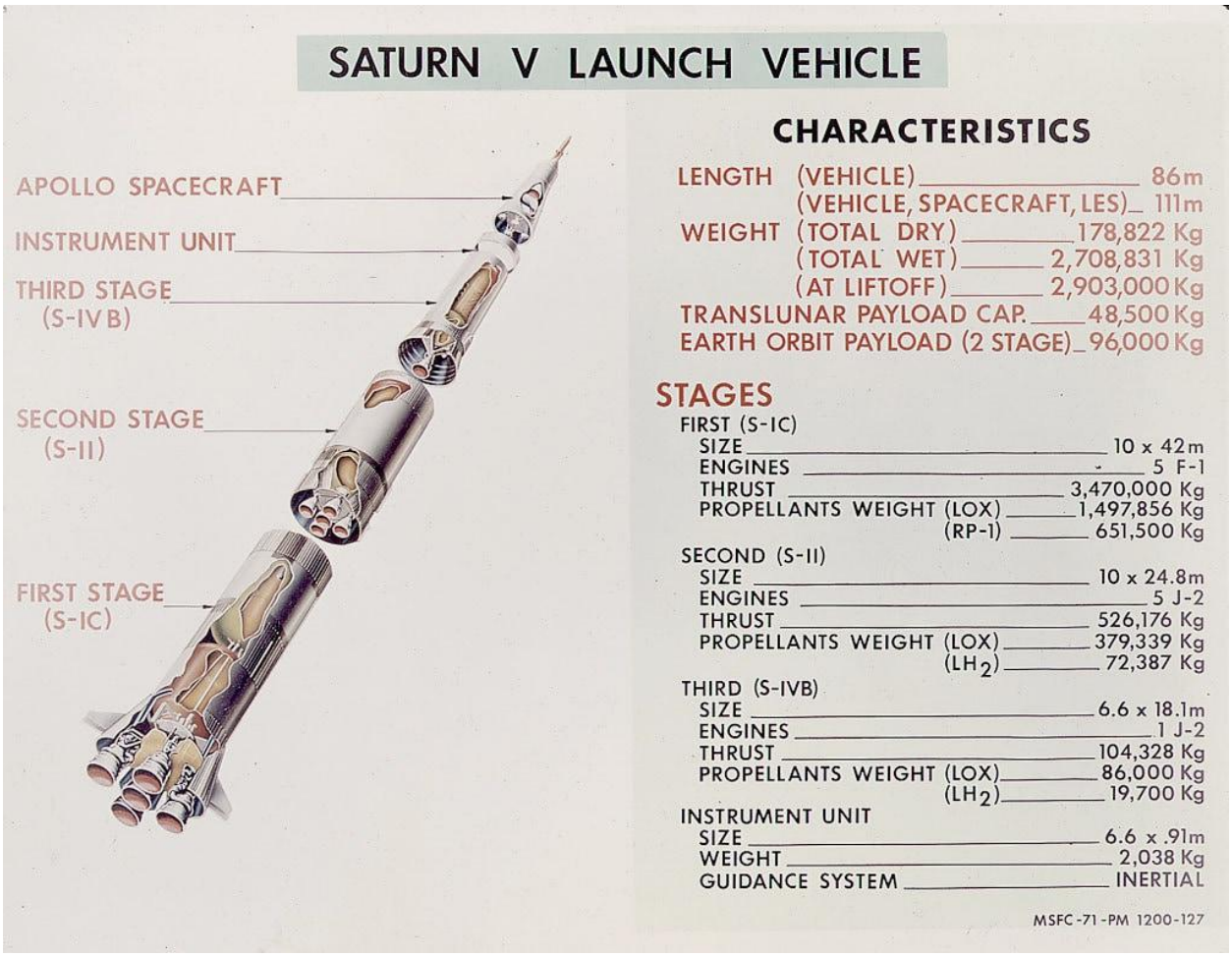
<u>So, how did humans visit the moon and return to earth?</u>

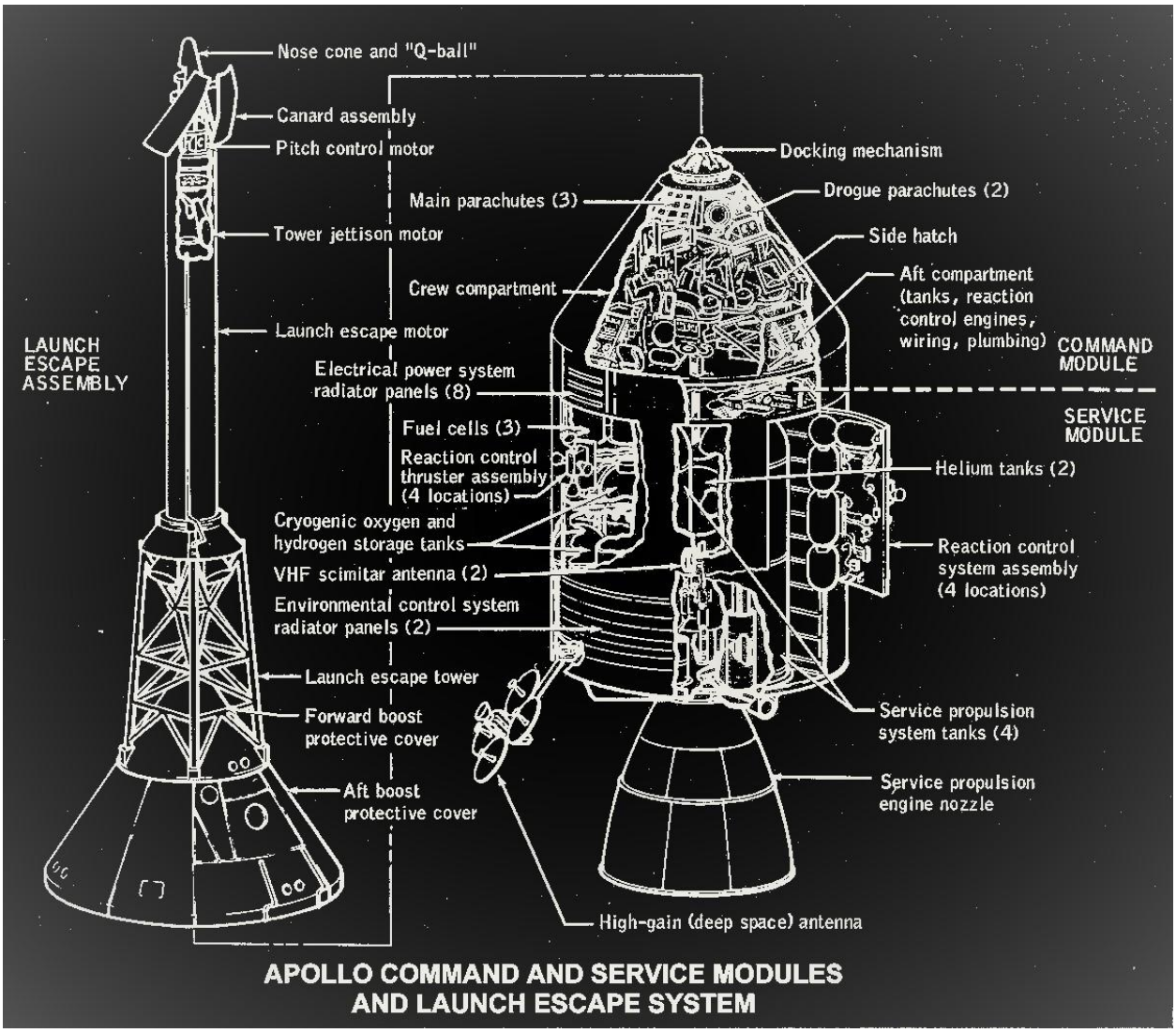
How did we manage to make a round trip to the moon faced with the daunting fuel factor of 5,561? A 12,000 kg ship would require 66,732,000 kg of fuel. This was out of the question. The idea of a simple ship traveling from earth to the moon and back to earth is absurd. And yet we did go to the moon and return. How was it done?

Workarounds had to be found for each leg of the trip. It took seven different spaceships to complete the journey, in which six of the ships were abandoned after use along the way. Of the original composite ship, 99.9% of the mass was used up as fuel or abandoned after use. Only a small space capsule containing three humans returned to earth and splashed down in the Pacific Ocean.

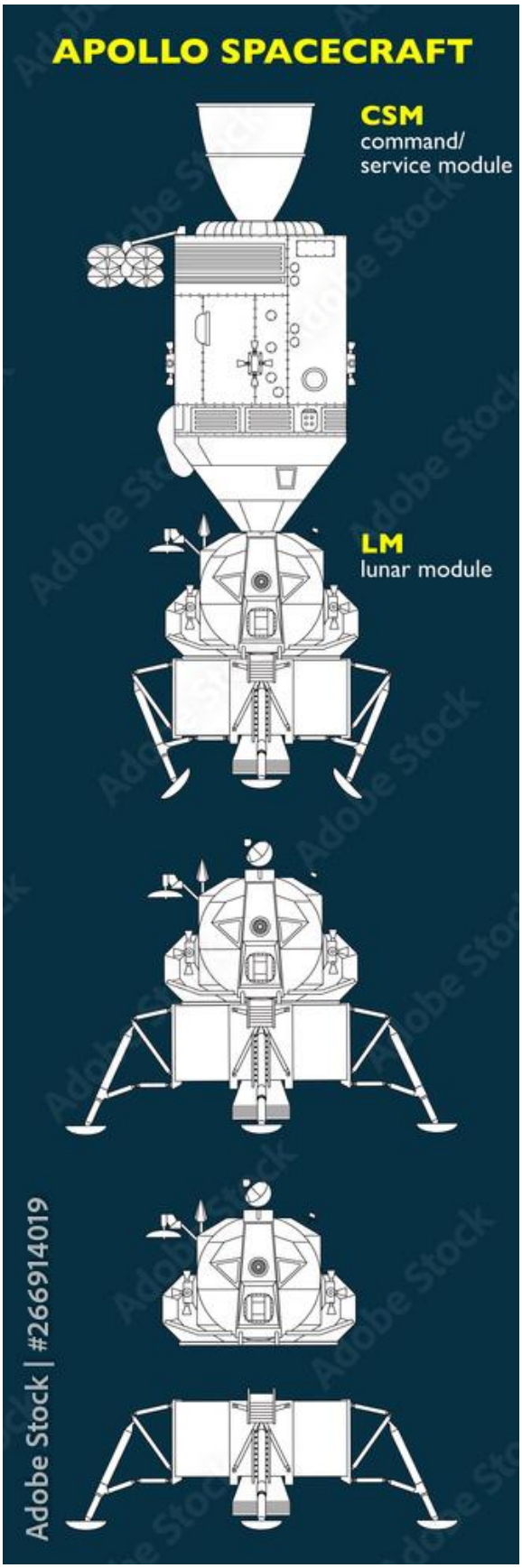
The original Saturn V/Apollo spacecraft had seven segments (eight if we count the small emergency escape section which was jettisoned soon after each successful launch). The first three segments were boosters used to get the whole contraption off the earth, into low earth orbit and then to kick the Command and Service Module (CSM) on its way to the moon at about 25,000 miles per hour. Earth's gravitational pull significantly slowed down the CSM. The average speed of the CSM to and from the moon was about 3,500 miles per hour. The CSM craft had its own rocket engine. It, in turn, initially consisted of four independent craft. First, the basic CSM. Second and third, the lunar descent and landing vehicle and the lunar ascent vehicle, which were initially attached to one another. Fourth, the earth landing capsule.


Apollo Spacecraft
Service Module
Command Module
Lunar Lander
Source: NASA


SATURN V LAUNCH VEHICLE
APOLLO SPACECRAFT
INSTRUMENT UNIT
THIRD STAGE (S-IVB)
SECOND STAGE (S-II)
FIRST STAGE (S-IC)
CHARACTERISTICS
LENGTH (VEHICLE) 86m
(VEHICLE, SPACECRAFT, LES) 111m
WEIGHT (TOTAL DRY) 178,822 Kg
(TOTAL WET) 2,708,831 Kg
(AT LIFTOFF) 2,903,000 Kg
TRANSLUNAR PAYLOAD CAP. 48,500 Kg
EARTH ORBIT PAYLOAD (2 STAGE) 96,000 Kg
STAGES
FIRST (S-IC)
SIZE 10 x 42m
ENGINES 5 F-1
THRUST 3,470,000 Kg
PROPELLANTS WEIGHT (LOX) 1,497,856 Kg
(RP-1) 651,500 Kg
SECOND (S-II)
SIZE 10 x 24.8m
ENGINES 5 J-2
THRUST 526,176 Kg
PROPELLANTS WEIGHT (LOX) 379,339 Kg
(LH2) 72,387 Kg
THIRD (S-IVB)
SIZE 6.6 x 18.1m
ENGINES 1 J-2
THRUST 104,328 Kg
PROPELLANTS WEIGHT (LOX) 86,000 Kg
(LH2) 19,700 Kg
INSTRUMENT UNIT
SIZE 6.6 x .91m
WEIGHT 2,038 Kg
GUIDANCE SYSTEM INERTIAL
MSFC-71-PM 1200-127



APOLLO COMMAND AND SERVICE MODULES AND LAUNCH ESCAPE SYSTEM


APOLLO SPACECRAFT
CSM
command/
service module
LM
lunar module
Adobe Stock | #266914019

Approaching the moon, the CSM used power to slow itself to a lunar orbit speed. Then the combined lunar descent/ascent vehicle landed under power. After spending time on the moon, the ascent vehicle separated from the descent vehicle and powered into lunar orbit and rendezvous with the CSM to transfer the two lunar astronauts who had landed on the moon's surface. The CSM then powered out of lunar orbit and toward earth. After initially slowing somewhat due to the moon's gravitational pull, the CSM came under the earth's gravitational influence and speeded up, reaching about 25,000 miles per hour as it neared earth. The earth landing capsule then separated from the CSM and fell to earth. Atmospheric resistance and later three parachutes slowed the capsule to about 20 miles per hour before it splashed down in the Pacific Ocean.

The effect of all this was to spread out the delta v of the moon and return trip among six disposable components of the original ship, the three boosters, the CSM, the lunar lander and the lunar ascent vehicle. The capsule with three humans aboard simply fell to earth slowed by atmospheric drag and finally three parachutes.

Numerically, the total delta v of the moon round trip of 29.32 was reduced by 11.44 since the return capsule simply fell to earth rather than returning under power. The remaining delta v of 17.88 was spread out among the disposable components of

the original ship. The return capsule with three humans aboard was about 1/1,000 of the original mass which left earth.

The latest plans for visiting the moon by NASA, China, SpaceX, the Amazon Blue Moon consortium and others all involve separating human transit to the moon and landing/ascent to and from the moon's surface. NASA's Orion vessel is to carry a crew to a high orbit around the moon, from which Orion will have enough power to escape the moon and return to earth. The landing/ascent vehicles will arrive separately and autonomously with no crew. Crew will transfer from Orion to the landing vehicle and land autonomously, but with backup manual controls available. The landing craft will reverse this process to deliver the crew to high moon orbit to transfer back to Orion for return to earth. This dual design is driven by the Rocket Equation. Combining a human transport vehicle with a large landing/ascent craft requires too much fuel. Apollo achieved both objectives with one composite vehicle only by making the Command and Service Module powerful enough to enter and leave a low moon orbit and a landing/ascent craft small enough for a powered landing and ascent with small cargo capability.

Obviously, this is not the way space travel is portrayed in science fiction movies and books, where a single ship flies around the solar system or beyond visiting planet after planet without any fuel problems.

What about travel to Mars?

Mars is our closest solar neighbor in terms of the delta v budget required for the trip at 36.62 using the Hohmann Transfer minimum energy trajectory. Could we follow a similar strategy as the moon trip to send humans to Mars and return them to earth?

The Mars round trip delta v is 36.62, only 25% greater than the moon round trip delta v of 29.32. Unfortunately, the fuel factor given by the Rocket Equation is 47,600 kg of fuel for every kg of the unfueled rocket mass. This is 8.6 times greater than required for the moon trip. This drastically alters the situation.

The clearest conceptual planning is that by the SpaceX Starship program.

The Block II specifications for the Starship are 85,000 kg of dry mass, 100,000 kg of payload, and 1,400,000 kg of fuel. We can calculate the Starship potential delta v, by rearranging the terms of the Rocket Equation, as equal to 3.4 ln (1,585,000/185,000) = 7.3 km/s.

The delta v needed to get into earth orbit is 9.0 km/s, so we have a problem right from the start.

This leads to the first workaround. A huge booster rocket with 33 Raptor-3 engines is used to get the Starship off the ground and partway toward earth orbit. After the booster exhausts its fuel and disconnects from Starship, the Starship's six Raptor-3 engines fire up and propel the craft into earth orbit, expending

about 95% of its 1,400,000 kg of fuel. This leaves the Starship in low earth orbit but with about 0.36 potential delta v remaining. This is not remotely near the 2.44 delta v needed to leave earth's gravitational well.

Now comes the second workaround, refueling Starship while in earth orbit to return its potential delta v to 7.3. This involves sending many fuel tankers into earth orbit. If each tanker can carry 100,000 kg of extra fuel, then refueling will require 14 tankers to add 1,400,000 kg of fuel to Starship. This is a massive and unproven undertaking. But, if successful, it restores the Starship to a potential 7.3 delta v.

The next leg of the trip is to fly to Mars and enter orbit around Mars. The minimum energy trajectory for this leg is the Hohmann transfer trajectory with two rocket burns, taking 8 ½ months of travel time and expending 5.7 delta v. Of this delta v, 3.6 is used for the travel to Mars and 2.1 is used to slow down at Mars to enter orbit around the planet. However, SpaceX plans to expend 4.3 delta v on the trip to Mars to get there quicker and taking a shorter route. Then the Starship is to use aerobraking at Mars to slow down and enter orbit, thus saving 0.8 delta v for his leg of the journey. At this point Starship has a remaining delta v of 3.0. A fully powered landing on Mars requires 3.6 delta v, so this is out of the question. The SpaceX plan is to again use aerobraking to slow the craft and then use just 1.41 delta v to power to a landing on the planet. This leaves Starship with 1.59 delta v in its tank, not nearly

enough to take off and enter orbit again, which requires 3.6 delta v.

Now comes the next workaround. Starship must carry with it fuel production and fuel transfer mechanisms to produce and transfer liquid methane and liquid oxygen to refill its tanks and return Starship's potential delta v once again to 7.3.

With the return trip to earth about 26 months away since it takes that long for Mars and earth to again approach one another closely, the crew must produce nearly 1,500 kg of fuel per day to add 1,100,000 kg of fuel to Starship needed for the takeoff from Mars and the return trip to earth. Estimates for the mass of a Sabatier plant of this capacity ranges from 75,000 kg to 150,000 kg, a burden for the Starship with a 100,000 kg cargo capacity. And this size Sabatier plant would require about three megawatts of continuous power to operate. A small nuclear plant able to generate this much power might have a mass of 10,000 kg, adding another burden to the cargo capacity of Starship.

If this workaround is successful, Starship will expend 3.6 delta v to get off Mars and enter orbit. With only 3.7 delta v remaining, Starship will have to follow a Hohmann transfer trajectory, using 3.6 delta v, as its only option to return to earth. This means an 8 ½ month journey back to earth.

With just 0.1 delta v left in the tank as it approaches earth, Starship plans to dive into the earth's atmosphere and again use aerobraking to achieve an earth orbit.

Once orbit is achieved, then there is one more workaround—you guessed it!—refueling Starship one last time, requiring many fuel tankers. With delta v restored once again to 7.3, Starship will dive deeper into the atmosphere and use more aerobraking to reduce its speed and then use 5.8 delta v to complete a powered landing on earth. This leaves 1.5 delta v of reserve fuel in the tank.

This is the only clearly specified and detailed plan for getting humans to Mars and back to earth.

It leaves a lot to be desired. And the margins for error are slim and deadly.

This only underscores the tyranny of the Rocket Equation. Without power, spacecraft are helpless and anyone aboard is stranded.

If this Starship scenario is the best we can do, then human space travel to Mars or beyond looks like a fool's errand.

This plan is somewhat like our earthly auto refueling operations when we take a trip across country, with one glaring exception. Auto travelers don't have to carry their own fuel production and transfer facilities and stop along the way to produce their own fuel.

<u>Beyond Mars?</u>

The next closest solar planet to earth in terms of delta v is Mercury, with a round trip delta v of 46.28 and a fuel factor of 815,670. This fuel factor is 17.2 times greater than that of Mars

and 147 times greater than the required for the moon round trip. And all the other solar system planets have even greater delta v requirements.

Small robotic spacecraft

Small craft with no humans aboard have been successfully sent to land and remain on Mars, although 50% to 60% of all landings fail. No craft has returned from Mars or attempted to return. A return scenario might one day be possible for a small robotic craft, however.

Conclusion

The point of this analysis is that large human-occupied spacecraft may never make a round-trip to Mars and back to earth.

And if Mars is out of reach for human travel, then so is every other planet in our solar system.

All this is made clear by the Rocket Equation and our current technology.

Can new technology make a difference?

No one has yet made a serious proposal for replacing chemical rockets with an equally powerful alternative. All the alternative proposals produce a tiny amount of thrust compared to chemical rockets and could be useful only in small, robotic craft in the vacuum of space with all the time in the world on their hands.

Delta-V Map of the Solar System

Black dots represent orbits, black lines represent burns
Blue numbers - Delta-V in km/s required to go from one node to the next
Red arrow - Aerocapture/aerobraking possible, reducing one-way delta-v

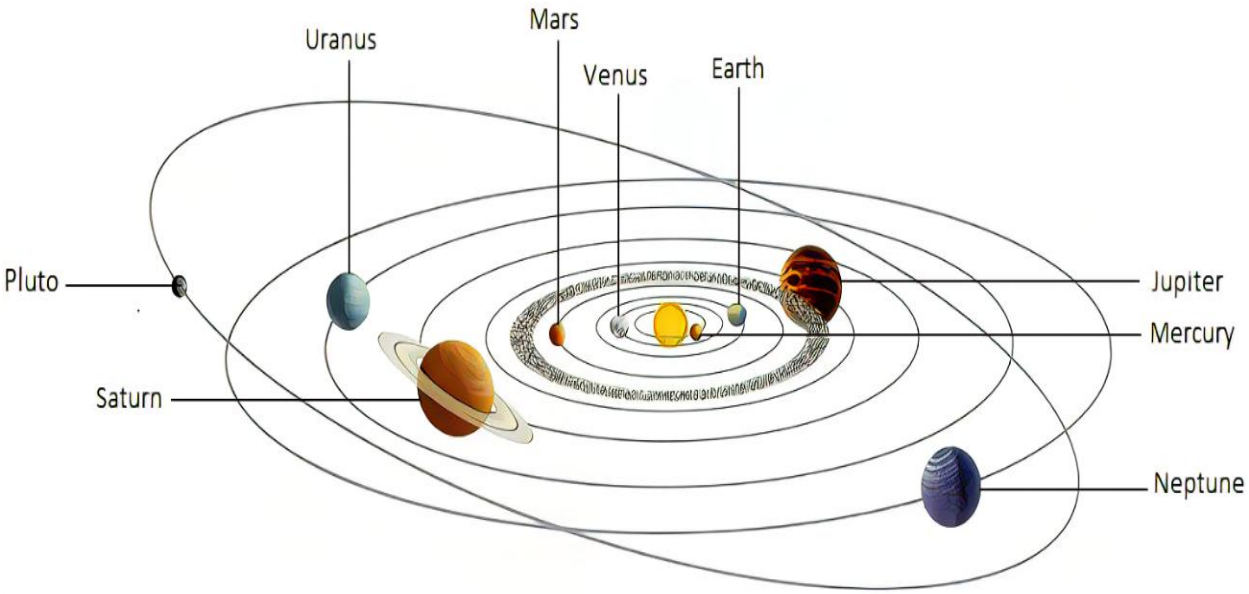
Inclination changes are not included.

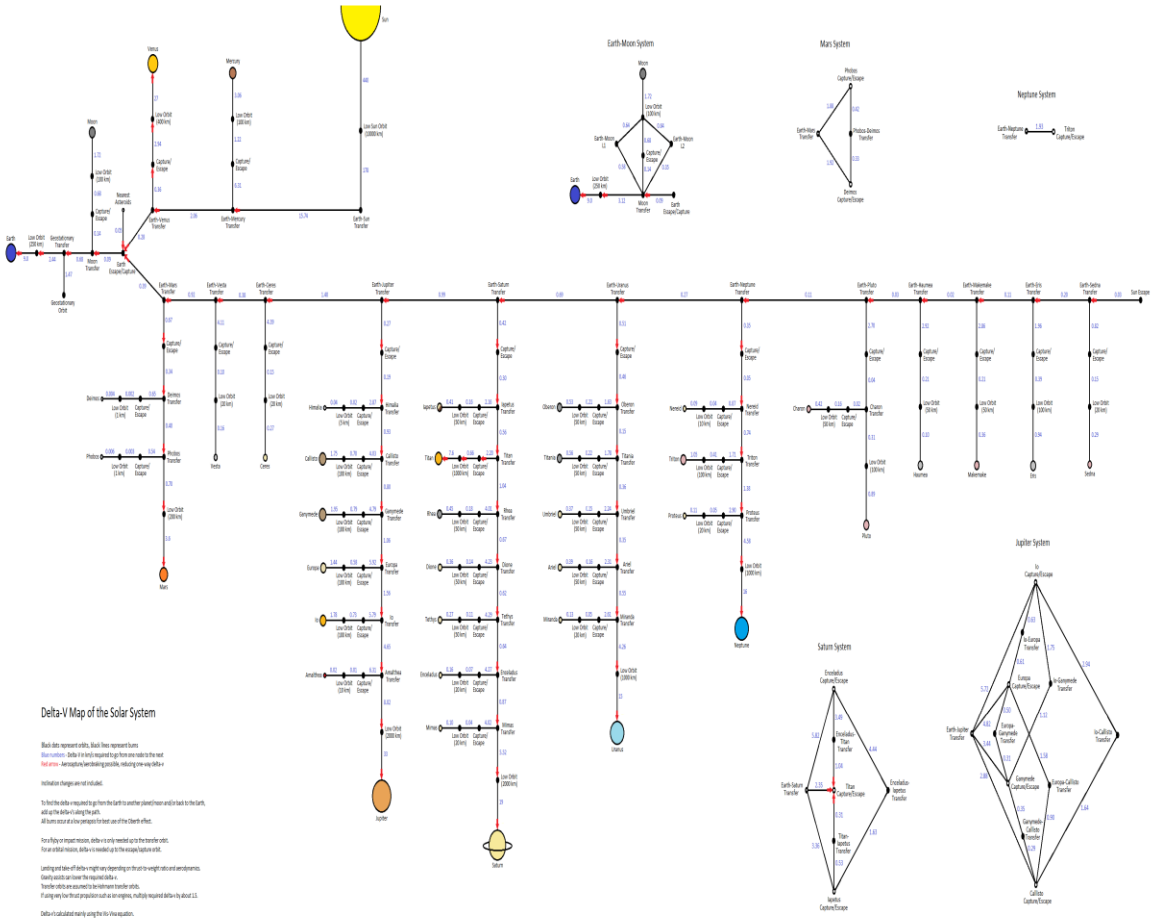
To find the delta-v required to go from the Earth to another planet/moon and/or back to the Earth, add up the delta-v's along the path.
All burns occur at a low periapsis for best use of the Oberth effect.

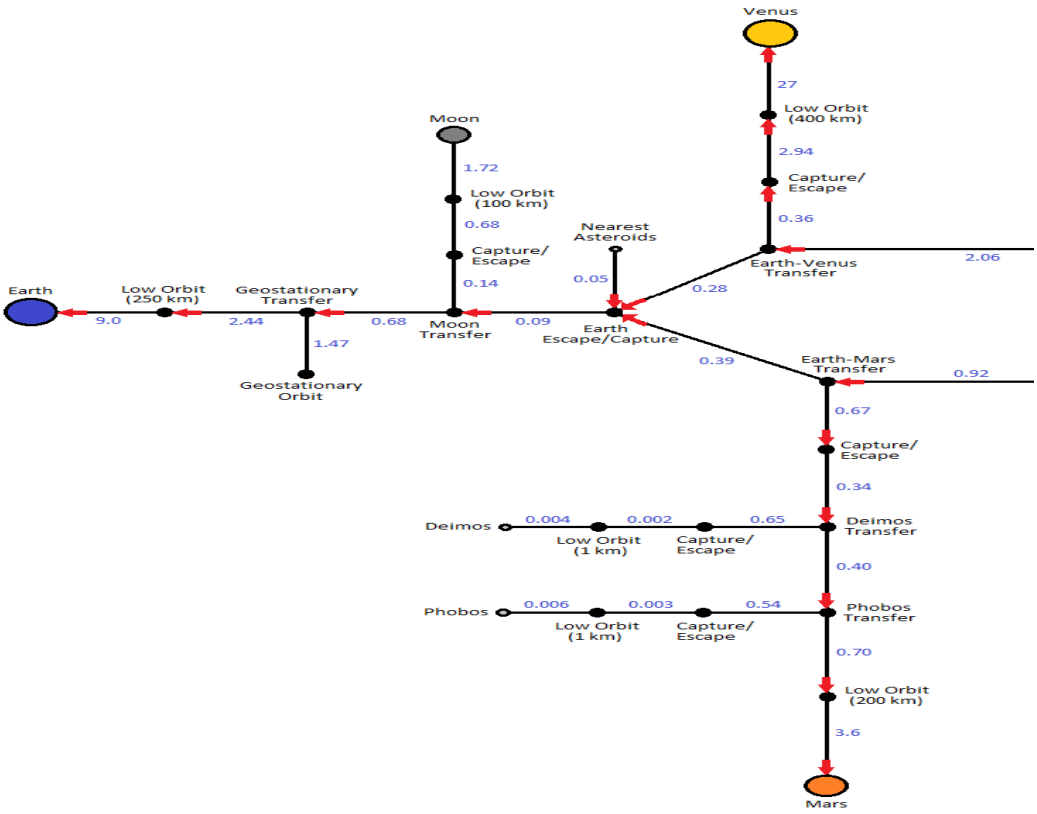
For a flyby or impact mission, delta-v is only needed up to the transfer orbit.
For an orbital mission, delta-v is needed up to the escape/capture orbit.

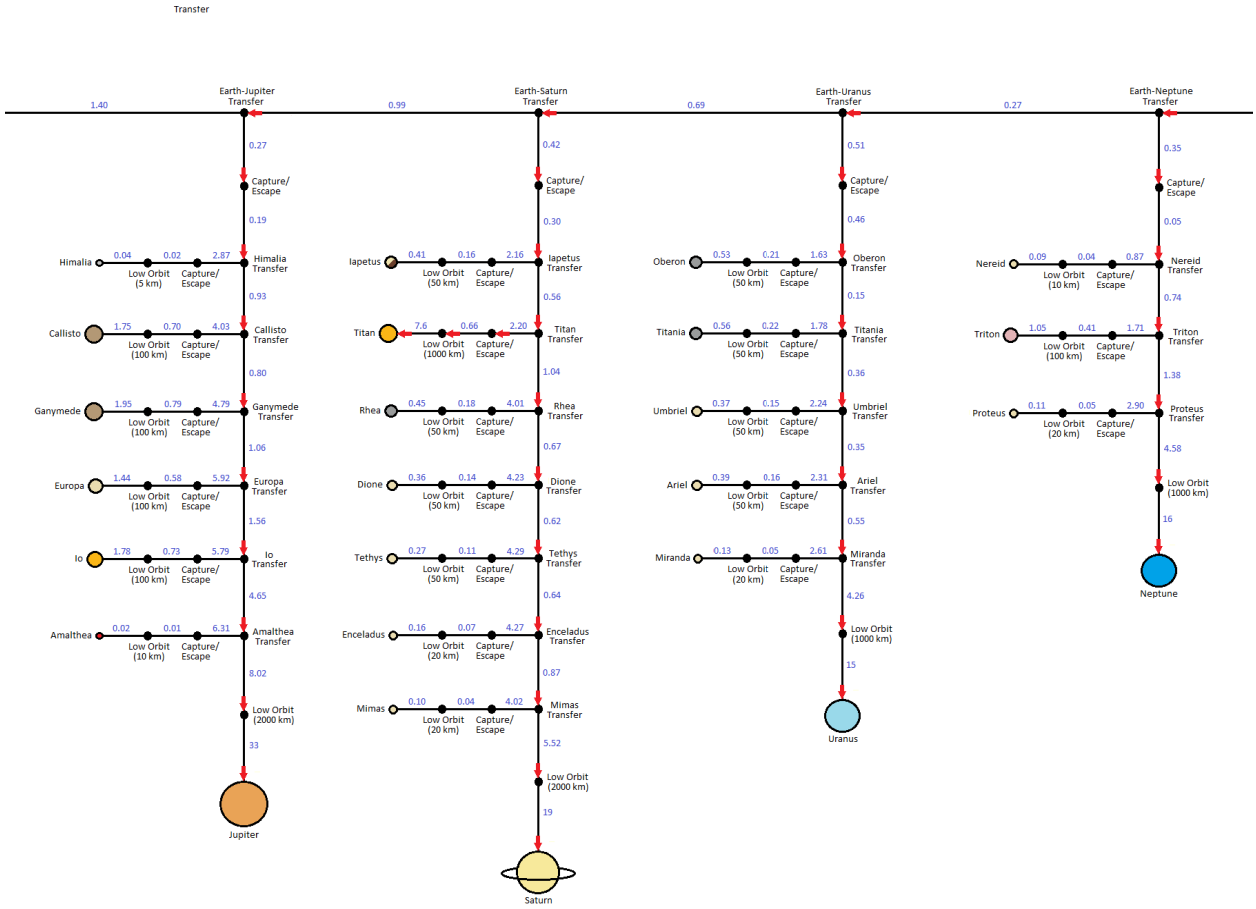
Landing and take-off delta-v might vary depending on thrust-to-weight ratio and aerodynamics.
Gravity assists can lower the required delta-v.
Transfer orbits are assumed to be Hohmann transfer orbits.
If using very low thrust propulsion such as ion engines, multiply required delta-v by about 1.5.

Delta-v's calculated mainly using the Vis-Viva equation.


Uranus
Mars
Venus
Earth
Pluto
Jupiter
Mercury
Saturn
Neptune


Earth-Moon System
Mars System
Neptune System
Saturn System
Jupiter System
Delta-V Map of the Solar System


Venus
27
Low Orbit
(400 km)
2.94
Capture/
Escape
0.36
Moon
1.72
Low Orbit
(100 km)
0.68
Capture/
Escape
0.14
Nearest
Asteroids
0.05
0.28
Earth-Venus
Transfer
2.06
Earth
Low Orbit
(250 km)
9.0
Geostationary
Transfer
2.44
1.47
Geostationary
Orbit
0.68
Moon
Transfer
0.09
Earth
Escape/Capture
0.39
Earth-Mars
Transfer
0.92
0.67
Capture/
Escape
0.34
Deimos
0.004
Low Orbit
(1 km)
0.002
Capture/
Escape
0.65
Deimos
Transfer
0.40
Phobos
0.006
Low Orbit
(1 km)
0.003
Capture/
Escape
0.54
Phobos
Transfer
0.70
Low Orbit
(200 km)
3.6
Mars


Transfer
Earth-Jupiter Transfer
1.40
0.27
Capture/ Escape
0.19
Himalia
0.04
0.02
2.87
Low Orbit (5 km)
Capture/ Escape
Himalia Transfer
0.93
Callisto
1.75
0.70
4.03
Low Orbit (100 km)
Capture/ Escape
Callisto Transfer
0.80
Ganymede
1.95
0.79
4.79
Low Orbit (100 km)
Capture/ Escape
Ganymede Transfer
1.06
Europa
1.44
0.58
5.92
Low Orbit (100 km)
Capture/ Escape
Europa Transfer
1.56
Io
1.78
0.73
5.79
Low Orbit (100 km)
Capture/ Escape
Io Transfer
4.65
Amalthea
0.02
0.01
6.31
Low Orbit (10 km)
Capture/ Escape
Amalthea Transfer
8.02
Low Orbit (2000 km)
33
Jupiter
Earth-Saturn Transfer
0.99
0.42
Capture/ Escape
0.30
Iapetus
0.41
0.16
2.16
Low Orbit (50 km)
Capture/ Escape
Iapetus Transfer
0.56
Titan
7.6
0.66
2.20
Low Orbit (1000 km)
Capture/ Escape
Titan Transfer
1.04
Rhea
0.45
0.18
4.01
Low Orbit (50 km)
Capture/ Escape
Rhea Transfer
0.67
Dione
0.36
0.14
4.23
Low Orbit (50 km)
Capture/ Escape
Dione Transfer
0.62
Tethys
0.27
0.11
4.29
Low Orbit (50 km)
Capture/ Escape
Tethys Transfer
0.64
Enceladus
0.16
0.07
4.27
Low Orbit (20 km)
Capture/ Escape
Enceladus Transfer
0.87
Mimas
0.10
0.04
4.02
Low Orbit (20 km)
Capture/ Escape
Mimas Transfer
5.52
Low Orbit (2000 km)
19
Saturn
Earth-Uranus Transfer
0.69
0.51
Capture/ Escape
0.46
Oberon
0.53
0.21
1.63
Low Orbit (50 km)
Capture/ Escape
Oberon Transfer
0.15
Titania
0.56
0.22
1.78
Low Orbit (50 km)
Capture/ Escape
Titania Transfer
0.36
Umbriel
0.37
0.15
2.24
Low Orbit (50 km)
Capture/ Escape
Umbriel Transfer
0.35
Ariel
0.39
0.16
2.31
Low Orbit (50 km)
Capture/ Escape
Ariel Transfer
0.55
Miranda
0.13
0.05
2.61
Low Orbit (20 km)
Capture/ Escape
Miranda Transfer
4.26
Low Orbit (1000 km)
15
Uranus
Earth-Neptune Transfer
0.27
0.35
Capture/ Escape
0.05
Nereid
0.09
0.04
0.87
Low Orbit (10 km)
Capture/ Escape
Nereid Transfer
0.74
Triton
1.05
0.41
1.71
Low Orbit (100 km)
Capture/ Escape
Triton Transfer
1.38
Proteus
0.11
0.05
2.90
Low Orbit (20 km)
Capture/ Escape
Proteus Transfer
4.58
Low Orbit (1000 km)
16
Neptune